

Gamma-Ray Pulsars: Modeling and Searches

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ABSTRACT. Using a likelihood analysis and EGRET detections, upper limits and diffuse background measurements, we find a best-fit luminosity law $L \propto P^{-1.7} B^{1.2}$ for the gamma-ray pulsar population. We find that roughly 30 of the 170 unidentified EGRET sources are likely to be pulsars. This is roughly twice the number of known radio pulsars which are plausibly associated with unidentified EGRET sources. We predict that AGILE will detect roughly 70 pulsars as point sources, including 12 which will be able to be detected in blind periodicity searches. GLAST should detect roughly 1200 pulsars (including only 200 currently known radio pulsars), 210 of which will be able to be detected in blind searches. We discuss methods of searching for pulsars in gamma-ray data and present results from our searches for gamma-ray periodicities from new radio pulsars associated with unidentified EGRET sources.

1. Introduction

Because pulsars emit the majority of their spin-down energy in gamma-rays, understanding their emission at these energies is crucial for forming a complete picture of pulsar energetics. However, while the radio pulsar population now numbers almost 1500, pulsed gamma rays have been detected from less than 10 sources. With these sparse statistics, addressing important issues such as how gamma-ray luminosity depends on spin-down parameters, the gamma-ray pulsar emission mechanism, the relationship between radio and gamma-ray beams, the pulsar contribution to the unidentified EGRET source population, and the pulsar science prospects of future gamma-ray missions is difficult. For this reason, we developed a likelihood analysis which uses the EGRET pulsar detections, upper limits, and diffuse background measurements to characterize some properties of the gamma-ray pulsar population. In this paper, we outline our updates to the analysis of McLaughlin & Cordes 2000 (hereafter MC00), present the new results, and discuss the prospects of AGILE and GLAST for pulsar science. We also discuss issues involved in searching for gamma-ray pulsars and present the methodology and results from searches for gamma-rays from new radio pulsars. Such searches are difficult due to the sparseness of gamma-ray photons and the lack of contemporaneous radio ephemerides.

2. Model

Our likelihood function is a product of the individual likelihoods for pulsar detections, upper limits and diffuse background measurements. We model a pulsar's gamma-ray luminosity L as a power-law in period P (in seconds) and magnetic field B_{12} (in units of 10^{12} G) such that $L = \gamma P^{-\alpha} B_{12}^{\beta}$. We assume a spin-down law with braking index n to calculate a population-averaged luminosity. To calculate all likelihoods we assume a broad beaming solid angle of 2π . To calculate the diffuse background likelihood, we assume a constant pulsar birthrate of 1/100 yr, a Galactic age of 10^{10} years, and a maximum gamma-ray efficiency of 1/2. We allow pulsars to contribute up to 10% of the total diffuse flux and assume that they are distributed in a Gaussian disk of scale 6 kpc with exponential halo of scale 0.5 kpc and molecular ring at 4 kpc with width 1.5 kpc. Please see MC00 for detailed descriptions of the likelihood calculations.

In MC00, we used the Taylor & Cordes (1993) electron density model to calculate pulsar distances. In this analysis, we use Cordes & Lazio (2002). This has not changed the results dramatically, but has been important for some individual objects. For example,

the implied gamma-ray efficiency for B1055–52 has decreased from 30% to 5%. In MC00, we assumed a single value for the population’s magnetic field B and initial spin period P_0 . In this analysis, we fit for a lognormal distribution for B characterized by mean $\langle B \rangle$ and rms σ_B and a flat distribution for P_0 bounded by $P_{0,min}$ and $P_{0,max}$.

3. Results

Our EGRET data (described in MC00) consist of 7 pulsar detections, 353 pulsed flux upper limits and 3 diffuse background measurements. We calculate the likelihood for a range of values for α , β , γ , n , $\langle B \rangle$, σ_B , $P_{0,min}$, and $P_{0,max}$ and find well-defined maxima in α , β , and γ of 1.7, 1.2, and 32.4. We cannot constrain n , $\langle B \rangle$, σ_B , $P_{0,min}$, or $P_{0,max}$ as for any reasonable values the pulsar contribution to the diffuse flux is $\ll 10\%$. As the best-fit luminosity law therefore only depends on detections and upper limits, it is independent of all assumptions aside from beaming solid angle and distance. Table I shows that our best-fit law is most similar to ones in which the luminosity is proportional to the voltage drop across the polar cap. It is not consistent with luminosity proportional to spin-down energy and is also quite different from the best-fit OSSE (McLaughlin et al. 2000) and radio (Arzoumanian et al. 2002) laws.

TABLE I
Comparison with Luminosity Laws

Law	P, B Dependence
EGRET best fit	$P^{-1.7} B^{1.2}$
$L \propto \Delta V$	$P^{-2} B$
$L \propto \dot{E}$	$P^{-4} B^2$
OSSE best fit	$P^{-8.3} B^{7.6}$
Radio best fit	$P^{-1.3} B^{0.4}$

We can use the best-fit law and the assumptions of Section 2 to calculate the gamma-ray flux distribution for a model population of pulsars (see Figure 1). To do this, we must assume values for n and for the B and P_0 distributions. For only five pulsars has n been measured, with values ranging from 1.5 to 3 (see Zhang et al. 2001 and references therein). We adopt $n = 2.5$, as measured reliably for the Crab (Lyne et al. 1993). Fitting a lognormal distribution to the magnetic fields (i.e. $B_{12}^2 = 10^{12} P \dot{P}$) of 1244 non-recycled pulsars, we find a mean of 12.1 G and rms of 0.65 G. P_0 has only be estimated for eight pulsars associated with supernova remnants with independent age estimates and/or measurable pulsar proper motions. With estimates ranging from < 14 ms for J0537–6910 to 139 ms for J0538+2817 (see Migliazzo et al. 2002, Kramer et al. 2003, and references therein), we adopt a flat distribution from 10 to 150 ms.

This analysis shows that, given EGRET’s point source sensitivity of 10^{-7} ph cm $^{-2}$ s $^{-1}$ $\sim 10^{32.9}$ ergs s $^{-1}$ kpc $^{-2}$ (for a spectral index of -2), EGRET should have detected roughly 40 pulsars as point sources. For a pulsed-search sensitivity of 6×10^{-7} ph cm $^{-2}$ s $^{-1}$ $\sim 10^{33.7}$ ergs s $^{-1}$ kpc $^{-2}$ (for a 2-week integration, a duty cycle of 1/2, and a minimum N_s^2/N_t of 50, where N_s is the number of source counts and N_t is the number of total counts), EGRET could have detected six pulsars in blind searches. Of the 170 unidentified EGRET sources, 73 are within 10 degrees of the Galactic plane and 47 are non-variable (McLaughlin 2001), suggestive of a pulsar origin and consistent with our estimate of 40 pulsars detected as point sources. We can also compare with the analysis of Kramer et al. (2003) which found that, of the 48 positional coincidences between radio pulsars and unidentified EGRET sources, 19 ± 6 are likely to be real. The estimate of 40 EGRET pulsars is dependent upon a beaming solid angle of 2π . For a beaming solid

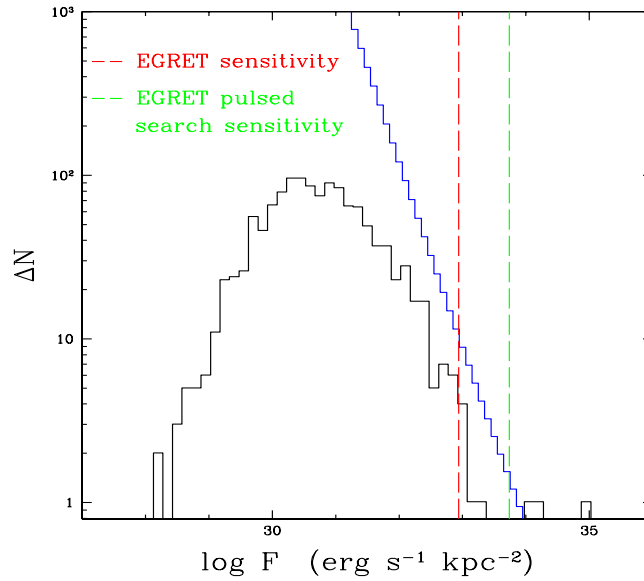


Fig. 1. The black line shows predicted fluxes for all 1244 non-recycled pulsars with measured P and \dot{P} . The blue line shows the predicted flux histogram for a model population of pulsars. Red and green lines show EGRET's sensitivity to point and pulsed sources.

angle of π , EGRET should have detected 20 pulsars as point sources. However, given the analysis of Kramer et al., this would imply that all pulsars detected by EGRET are currently known radio pulsars, a hypothesis which seems unlikely given that we know of at least one gamma-ray pulsar (Geminga) which is not detected at radio wavelengths.

In Table II, we list all radio pulsars with high model-predicted fluxes that are associated with unidentified EGRET sources¹. Six of these 12 pulsars have been detected in the Parkes Multibeam Pulsar Survey, which has discovered half of the 80 radio pulsars with ages < 100 kyr. We also list the EGRET fluxes (in units of 10^{33} ergs s^{-1} kpc^{-2}) and variability indices (McLaughlin 2001) of these sources. While all of the known EGRET pulsars have non-variable fluxes, some of these unidentified EGRET sources appear to be highly variable. It is difficult to determine whether these are spurious coincidences or if there is indeed some method through which pulsars may produce variable gamma-ray emission. One method is through searching for gamma-ray pulsations (see Section 4).

Given the expected sensitivities of AGILE and GLAST, we can predict the pulsar populations that each instrument will see. In Table III, we list the sensitivities (in units of 10^{31} ergs s^{-1} kpc^{-2}), and the numbers of expected detections of pulsars as point sources and in blind periodicity searches. In column two, the number of known radio pulsars that are expected to be detected is listed in parentheses (i.e. for EGRET, our model predicts that 17 out of the 40 total pulsar detections are known radio pulsars). In column four, the number in parentheses lists how many EGRET unidentified sources could be identified as pulsars in a blind periodicity search. These are optimistic estimates as they assume a 2-week, on-axis exposure with fresh gas. Note that GLAST will be able to detect pulsations from ALL of the unidentified sources in blind periodicity searches,

¹ J1747–2958 actually lies outside of the 95% position confidence contour of 3EG J1746–2851. However, because of diffuse model and positional uncertainties, especially towards the Galactic center, we believe this is a possible association.

unambiguously determining their nature. All of the estimates in Table III depend on a beaming solid angle of 2π and will decrease linearly with decreasing solid angle.

4. Gamma-Ray Pulsar Searching

With many pulsars expected to be detected at gamma-ray energies but not at radio wavelengths, developing methods to search for gamma-ray periodicities is crucial. We are applying such methods to search EGRET data for gamma-rays from the new radio pulsars listed in Table II. While we have current radio ephemerides for these objects, they are too imprecise to allow extrapolation back to the time the data were taken. Therefore, searching over a wide range of frequency f and frequency derivative \dot{f} , centered around those predicted by the current ephemeris, is necessary. To calculate the range to search, we assume errors in f and \dot{f} of roughly 10^{-8} s^{-1} and 10^{-12} s^{-2} , typically many times greater than the quoted timing errors, to account for glitches and timing noise. We space trial values of f and \dot{f} so that the smearing in the final folded profile is $< 10\%$ of the period. For each trial, we barycenter all photons to the pulsar's position and fold all those with energies $E_\gamma \geq 100 \text{ MeV}$ within an energy-dependent acceptance cone of radius $\theta \leq 5^\circ.85(E_\gamma/100\text{MeV})^{-0.534}$, weighting photons by the PSF (e.g. Ramanamurthy et al. 1996). We compute the significance of each profile using χ^2 , H (e.g. de Jager 1994), and Z^2 (e.g. Buccheri et al. 1983), normalizing by the number of trials, and inspect the most significant signals as determined by all of those three methods.

We have applied this method to all of the pulsars listed in Table II and to the known EGRET pulsars B0531+21 and B1706-44. For these known pulsars, we use ephemerides based on only 2 yrs of radio data for comparison with the timing solutions of similar timescale for the new pulsars. Examining the known pulsar results show that our inclusion of all photons above 100 MeV is optimal for detection; a lower cutoff results in less significant detections due to increased background photons but higher cutoffs result in too few pulsar photons. We find that for both known pulsars and in all viewing periods (VPs), weighting by the PSF increases the significance of detections. We find that χ^2 , H , and Z^2 generally return the same values for best f and \dot{f} but that both H and Z^2 return incorrect values for B0531+21 in some VPs where the pulsar is weak.

For each pulsar in Table II, we have searched all VPs for which the pulsar is less than 10° off-axis, with the number searched given in Table II. Using f and \dot{f} errors as quoted above, we only detect B0531+21 in the last seven of 14 VPs. Widening the range of f and \dot{f} searched, we detect the pulsar in all VPs. While B0531+21 is strong enough that it is still the most significant signal over the wider range, this would not be the case for the new pulsars. We detect B1706-44 in two of four VPs. If we do not use PSF weighting, only one of these detections is significant. Generally, detection significance for the B0531+21 and B1706-44 trials varies as expected with exposure time and off-axis angle, but we do not detect B1706-44 in one viewing period which has similar exposure and off-axis angle to another in which it is detected with high significance. For comparison, J1706-44 has a flux just less than that of 3EG J1746-2851 but higher than those of the other unidentified sources listed in Table II.

From two of the Table II pulsars, we detect tantalizing signals. In three of the 14 VPs searched for J1747-2958, the highest significance periodicities have similar pulse profile shapes (see Figure 2). This unique shape is not seen in any observations of any other pulsars. While the component amplitude ratio and widths vary for the different VPs, we see similar variations for the B0531+21 detections. It is unclear why this periodicity is not seen in any of the other VPs. The timing model may not be accurate enough to extrapolate to the earliest VPs, but there are some VPs between the first and second detections in which we would expect to see the signal but do not. This may be due to variations in the flux of the source. Similarly, in two of the eight VPs analyzed for J2021+3651, we detect high significance periodicities with similar profile shapes (see

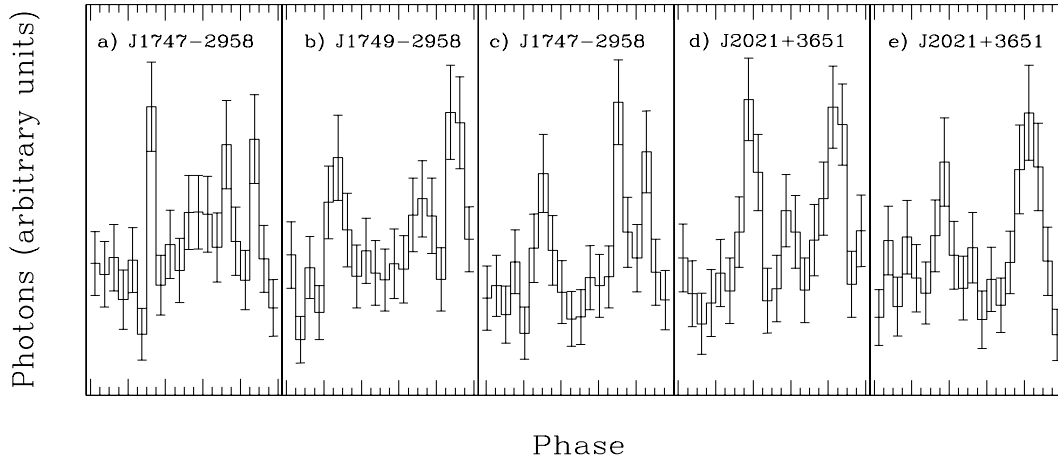


Fig. 2. Folded profiles, aligned to show shape similarities. Table IV lists the VPs, dates, observation lengths (in days), number of photons, and off-axis angle (in degrees) for each detection.

Figure 2). Again, why we do not detect the pulsar in other VPs is unclear. While we are working on more thorough analyses of these pulsars, determining whether they are in fact gamma-ray pulsars may have to wait for future observations with a current radio ephemeris. From several other pulsars in Table II we detect marginally significant periodicities. However, none of the profile shapes are repeatable across VPs.

5. Future

There are several improvements that we would like to make to our current population model. Obviously, all pulsars will not beam towards us with the same solid angle. While we believe that this assumption is sufficient for making the large-scale predictions of Table III, it does not allow us to explain the detection or non-detection of individual objects. We would also like to incorporate a more realistic pulsar spatial distribution, incorporating spiral arms. This will not make a large difference for the EGRET and AGILE detection statistics but may be important for GLAST, which will probe the population of weak, distant pulsars. Our model currently ignores gamma-ray emission from millisecond pulsars. But with the Kuiper et al. (2000) announcement of a probable detection of pulsed gamma rays from pulsar J0218+4232, this issue must be understood, as it could be important for the detectable populations of AGILE and GLAST. Finally, before the launch of GLAST and AGILE, we must further optimize pulsar search techniques so that we determine the most efficient ways of performing blind searches for gamma-ray pulsars on these data.

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TABLE II
Plausible Associations Between Pulsars and Unidentified EGRET Sources

Pulsar	3EG Source	F_γ	V	N_{vp}
J1747–2958	3EG J1746–2851	10.7	2.80	12
J1637–4642	3EG J1639–4702	8.8	1.88	5
J1413–6141	3EG J1410–6147	7.5	0.72	4
B1823–13	3EG J1826–1302	6.6	5.89	4
J1420–6048	3EG J1420–6038	6.2	1.14	5
B1853+01	3EG J1856+0114	6.2	1.32	2
J1837–0604	3EG J1837–0606	6.0	2.81	4
J1015–5719	3EG J1014–5705	5.5	0.55	7
J2021+3651	3EG J2021+3716	5.4	2.5	8
J1105–6107	3EG J1102–6103	5.2	2.38	7
J1016–5857	3EG J1013–5915	5.0	0.15	7
J2229+6114	3EG J2227+6122	4.4	0.19	2

TABLE III
Number of Expected Detections for Various Instruments

Instrument	Point S_{min}	Point Detections	Pulsed S_{min}	Pulsed Detections
EGRET	90	40(17)	550	6(10)
AGILE	45	70(25)	275	12(52)
GLAST	3	1200(200)	25	210(170)

TABLE IV
Possible Pulsar Detections

	Pulsar	Viewing Period	Date	Length	N_p	Off-Axis Angle
a)	J1747–2958	4210	Jun 1995	6.8	2395	4.0
b)	J1747–2958	5080	Dec 1995	7.2	2194	7.2
c)	J1747–2958	6250	Aug 1997	14.0	3597	2.3
d)	J2021+3651	0020	Jun 1991	8.2	8902	3.1
e)	J2021+3651	3181	Feb 1994	7.0	1934	6.8